Galaxy Formation and Evolution

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Talk Structure

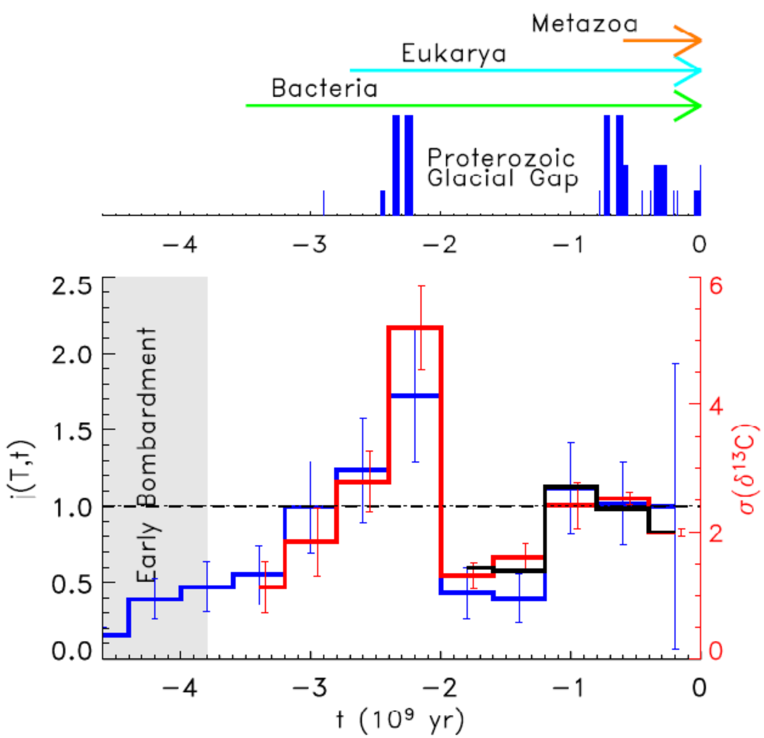
- **Has galaxy formation anything to do with Earth or life on it?**
- **Numerical Simulation of spiral structures of galaxies**
- **(Numerical Simulation of galaxy formation)**

Bottom Line:

Numerical simulation of galaxy formation/evolution is revolutionalizing the understanding of the spiral structures, and that might have deep implication on the galactic effect on our solar system.

Has galaxy formation anything to do with Earth or life on it?

Svensmark(2006): Starbursts in Milky Way Galaxy and Glaciation are related?



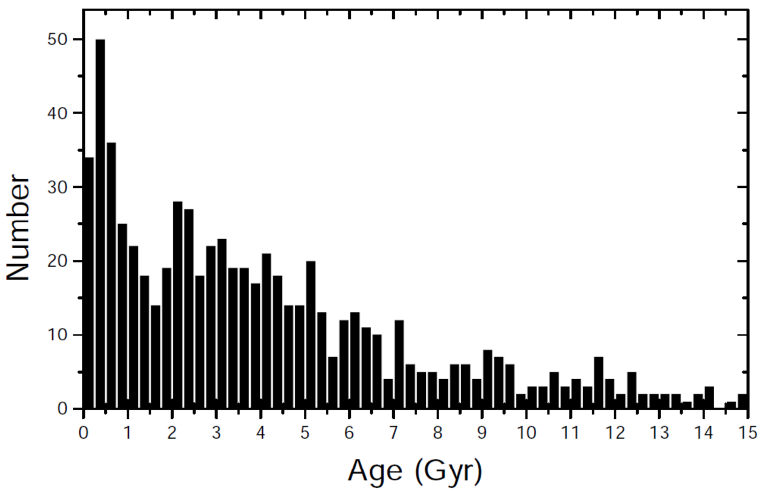
Blue: Cosmic Ray Level from star formation history
Red: $\delta^{13}C$ fluctuation

Burst in 2.x Gyrs ago related to glaciation?
0.8 Gyrs?
0.3 Gyrs?

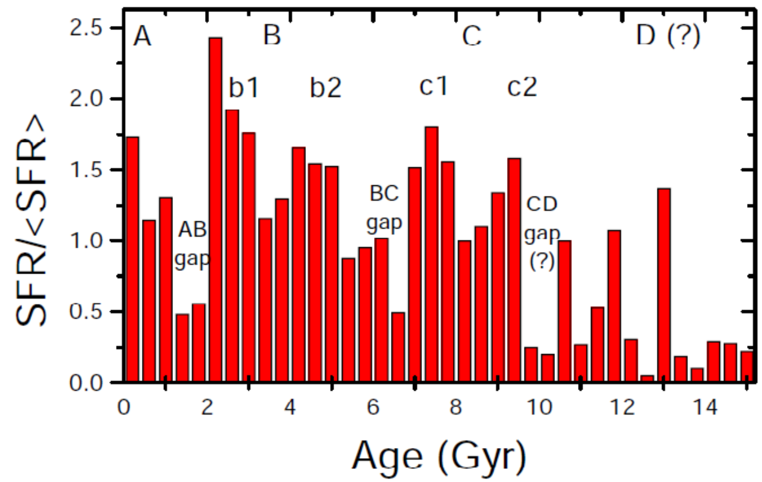
Do we really know the star formation history?

Reconstruction of Star Formation Rate (SFR)

Rocha-Pinto et al. (2000a,b)

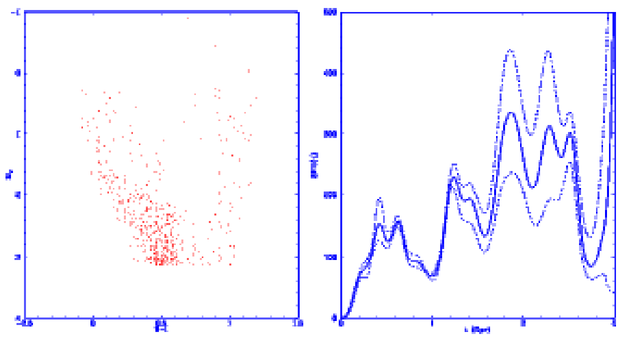


Original Data

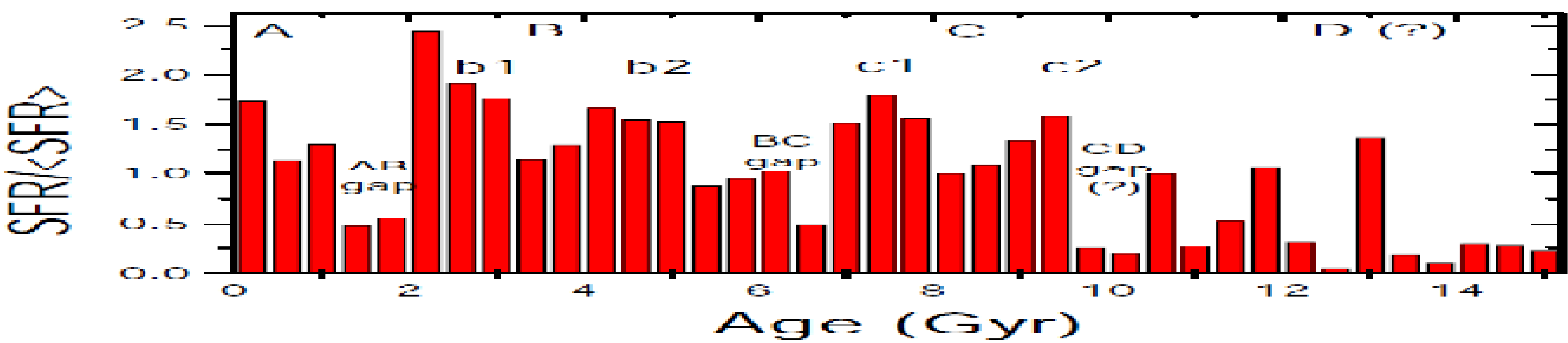


SFR after lots of "corrections"

Comparison with other works



Hernandez et al. 2000
Based on HIPPARCOS Catalog (pretty accurate distance based on trigonometric parallax.



Some features show agreement.

Why the difference?

- Different methods to estimate stellar ages
- Small number statistics (10-20 stars/bin)

Other sources of error

- Scale height correction
- Spiral and other structures of galaxy

For Cosmic Ray intensity

- Global SFR/Solar neighborhood SFR difference
- Initial Mass function.... Fraction of stars ended up in SN may depend on SFR itself
- Sun's vertical oscillation

We have no clue on how large these errors are.

More fundamental questions

- Does HIPPARCOS data tell anything about "global" starbursts?
- Isn't local variation more important for Earth and life?

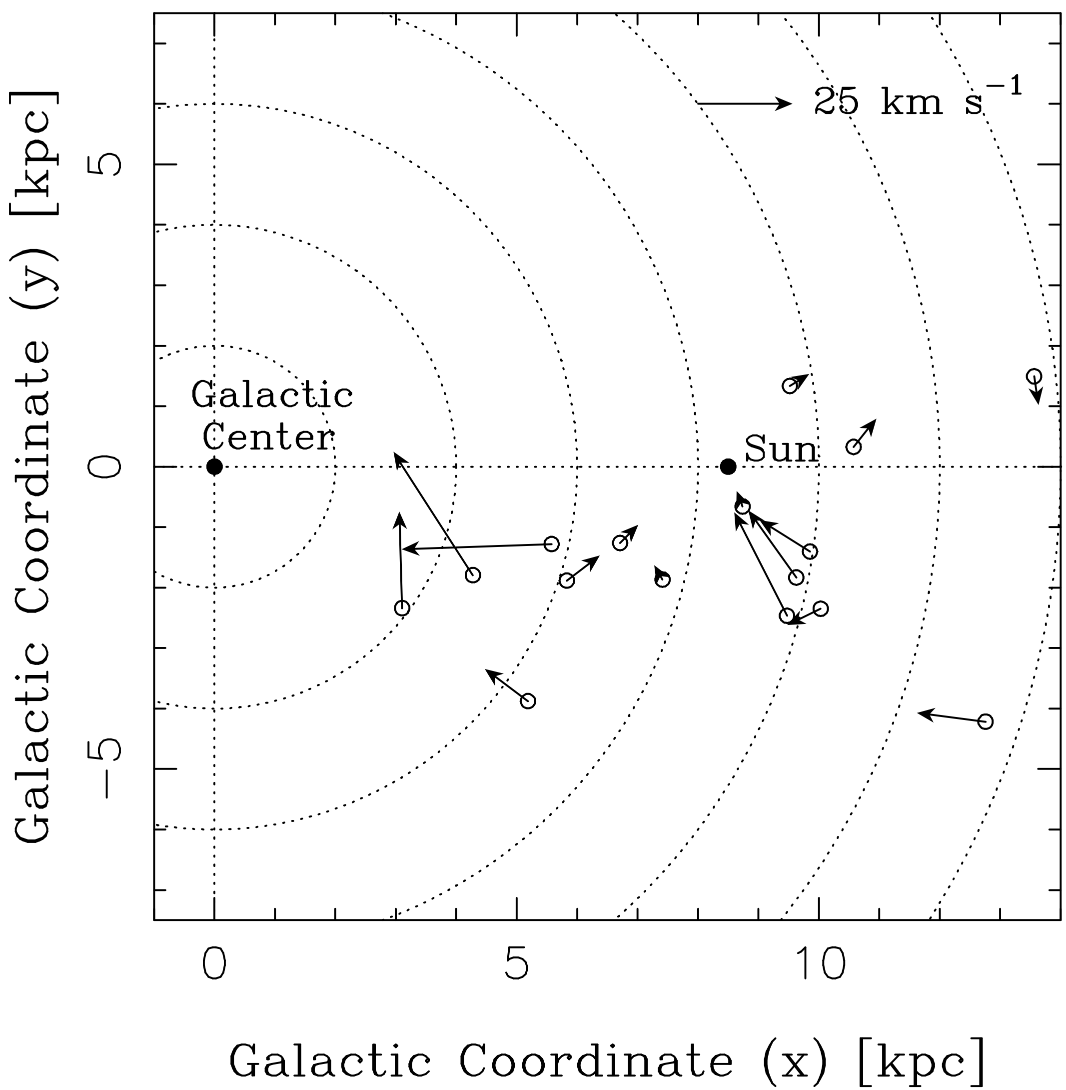
Questions difficult to answer from observation alone. We need to understand:

- How the spiral structure of our galaxy is maintained
- How Sun moves in our galaxy

Our galaxy — recent observation

- **VLBI distance measurement: Science (Xu et al, Science 311, 54)**
- **"Burst of papers on Nov 2008**
- **Additional results with VERA(Japanese VLBI astrometry project)**

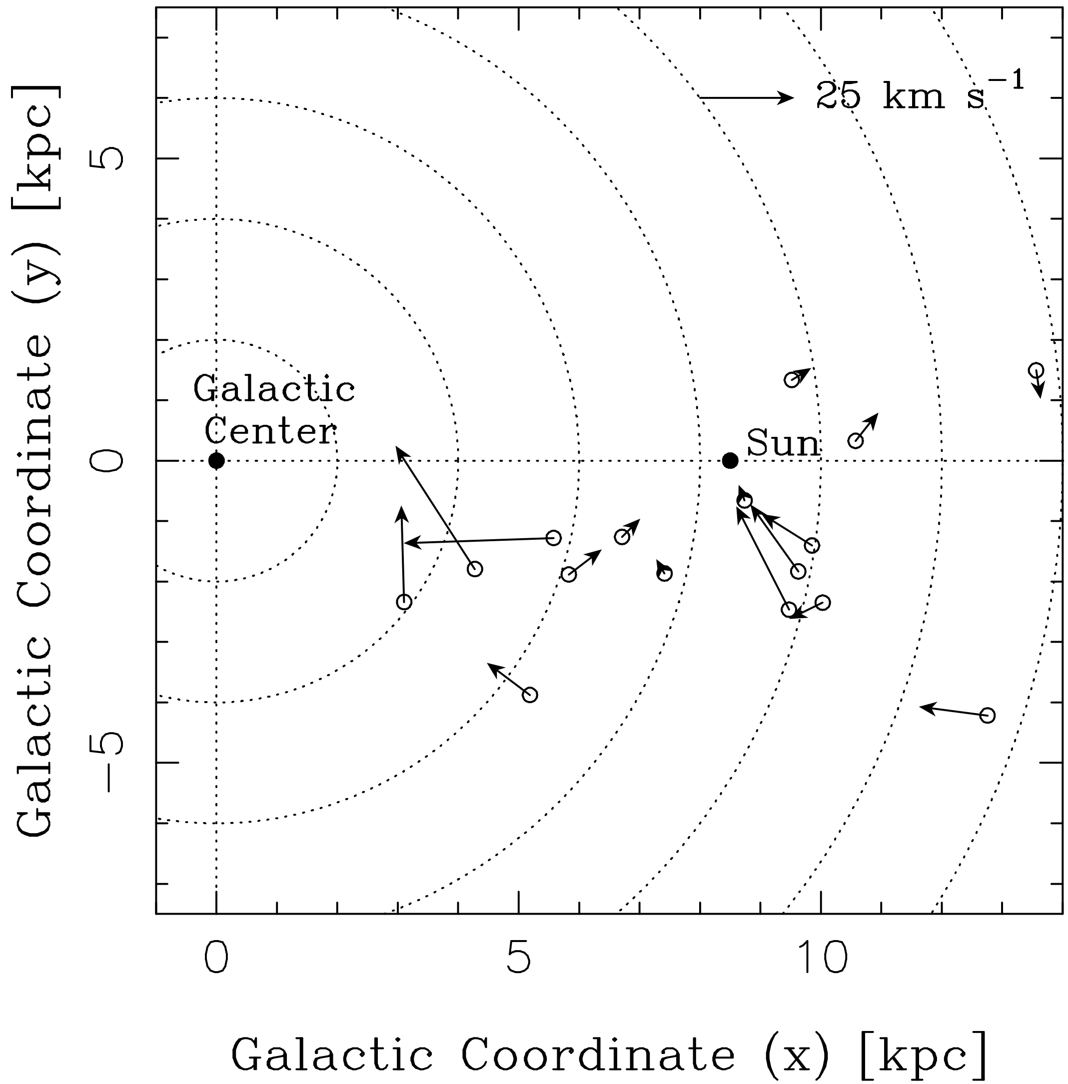
All (as of 2009) data combined



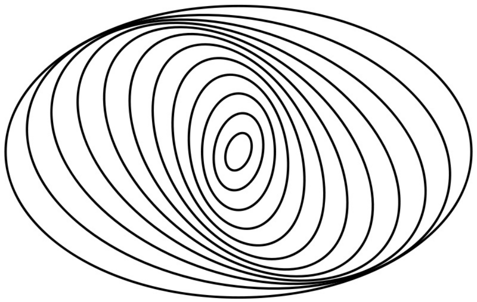
Our galaxy — recent observation

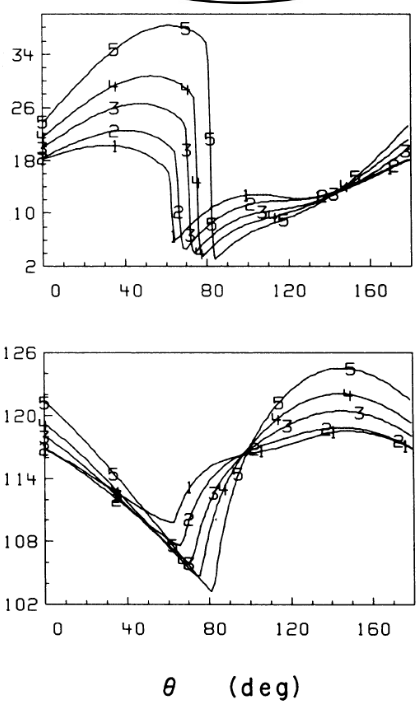
- **Very large non-circular motions (30km/s typical)**
- **Signs of spacial correlation?**

Is the classical density wave theory okay?



What is the density wave theory?





- Spiral structure is not a “material” entity but linear mode with neutral stability
- gas forms shock when it passes through the spiral arm, is compressed and star formation is triggered.
- Even with extremely massive spiral arms, non-circular motion with 10km/s is unlikely
- non-circular motion is near constant along one arm.

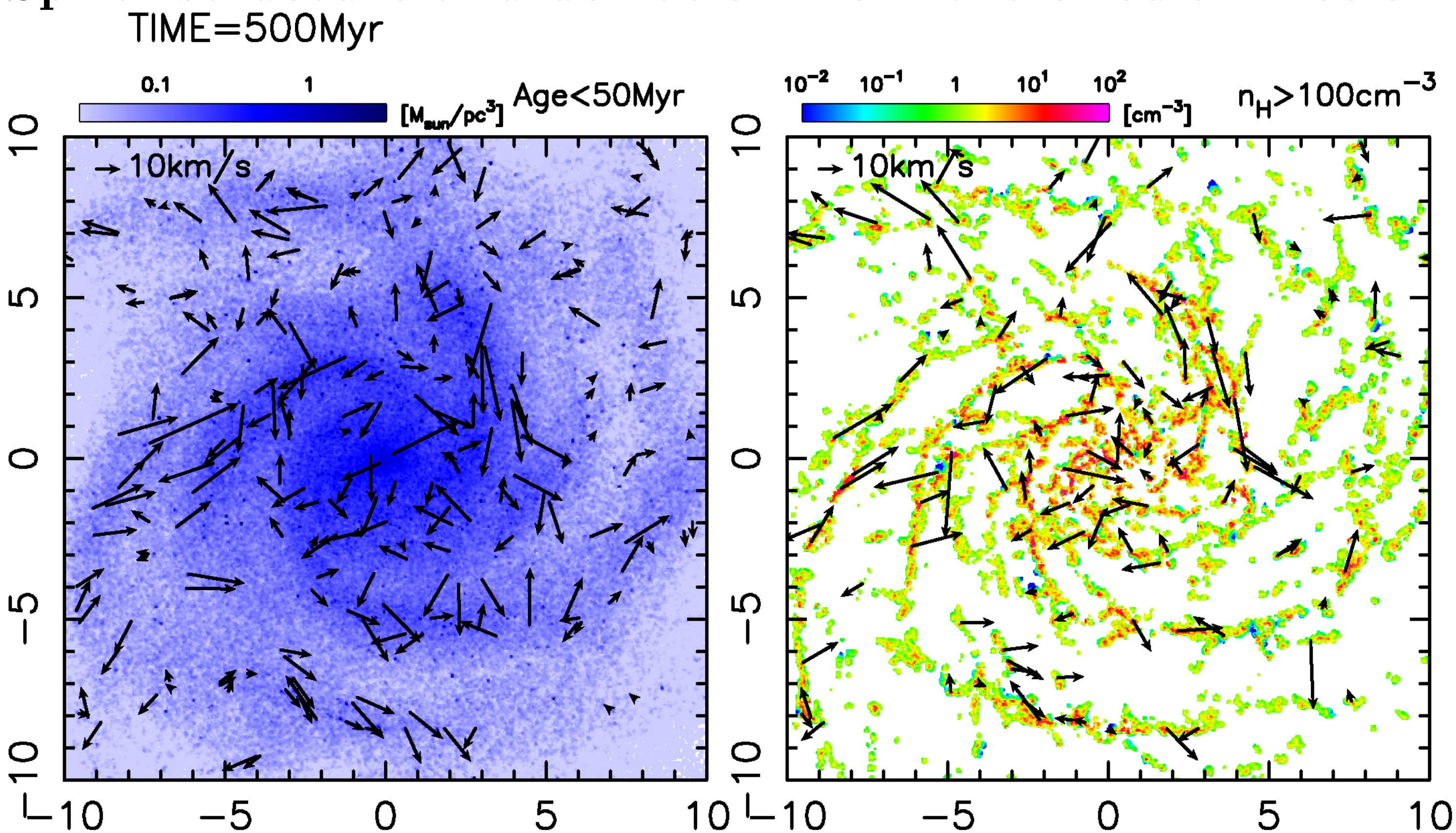
Seems to be completely different

Modern simulation of Galactic disk

(Baba et al 2009)

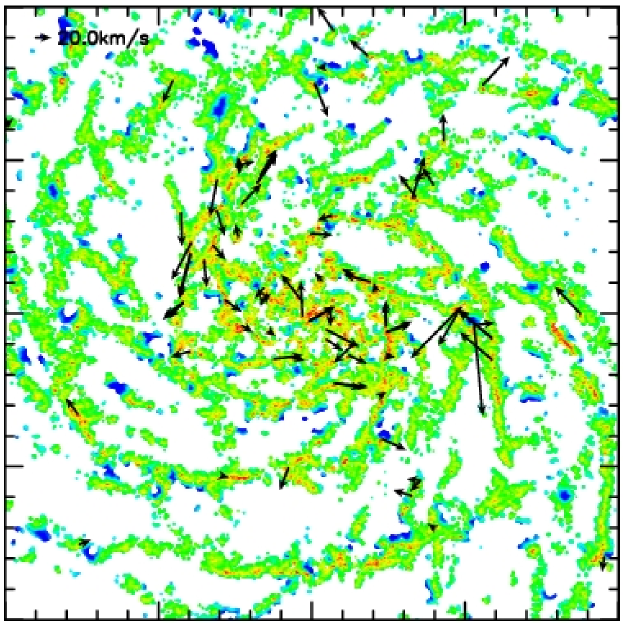
animation 1 2 3)

Spiral structure and deviation from the circular motion

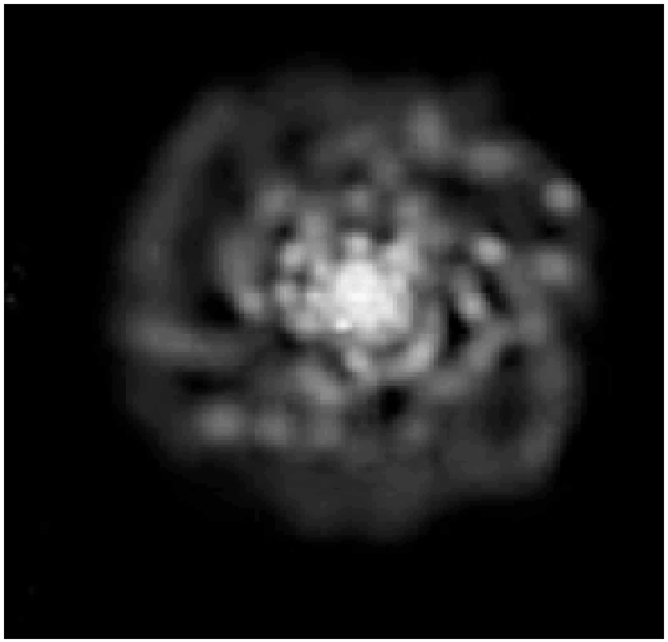


Left: distribution of stars Right: cold gas

High-resolution model and observation



Low-resolution model and observation



Why such differences?

Previous works

- **Spacial resolution $\gg$ 100pc**
- **Gas temperature kept $\geq 10^4$K**
- **stars form at $\rho \geq 0.1\mathrm{cm}^{-3}$**

These were necessary to avoid numerical difficulties.

Our calculation

- **Spacial resolution $\sim$ 10pc**
- **Gas temperature can go down to 20K**
- **stars form at $\rho \geq 100\mathrm{cm}^{-3}$**

We made many improvements in numerical methods to concur numerical difficulties. (Saitoh and Makino 2009, 2010, ...)

Motion of stars

motion of stars
motion in $E - L_z$ plane

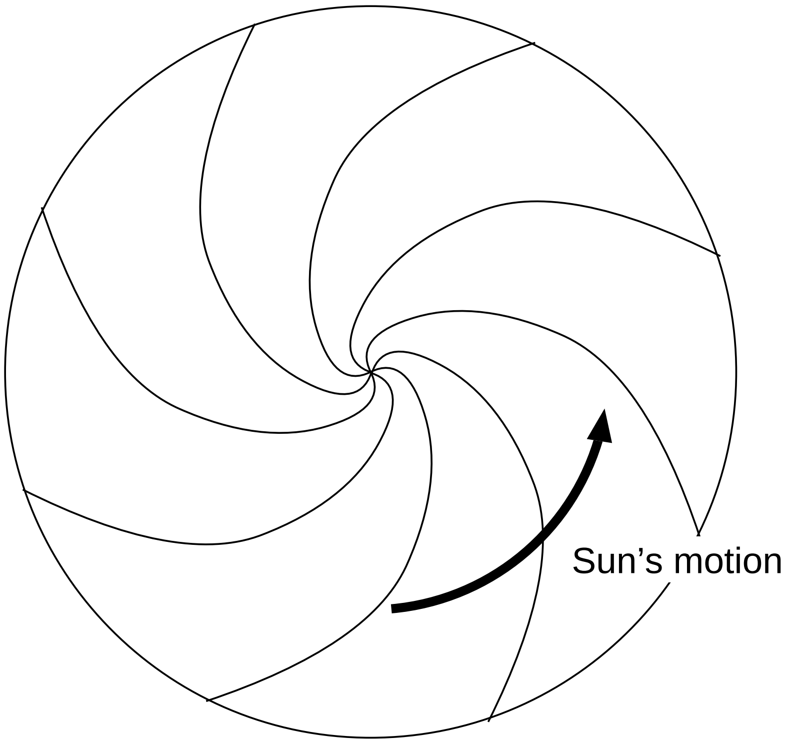
- **Spiral arms are continuously recreated**
- **Radial movement of stars can be large (several kpcs)**
- **Velocities are not so large**

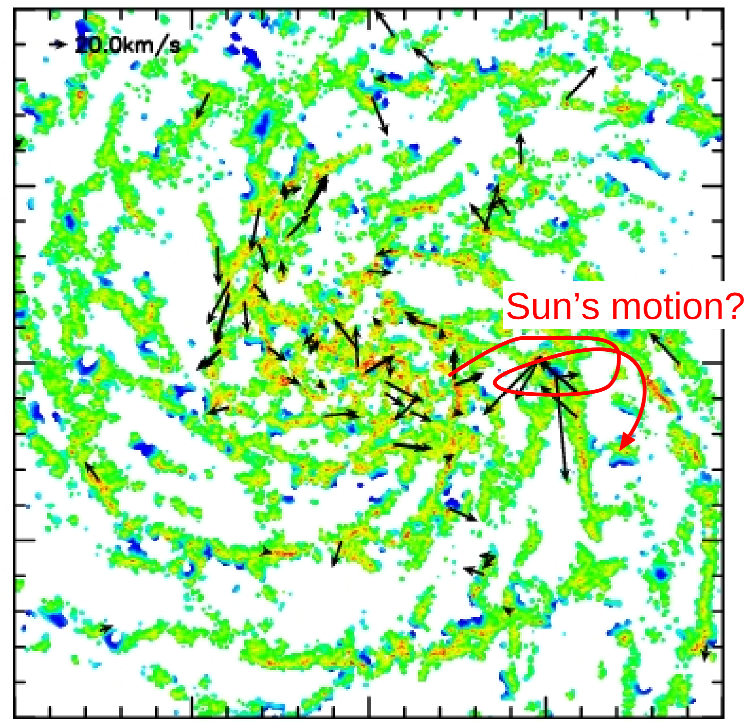
Pure stellar disk simulation

(Fujii et al 2010)
Animation a1
Animation a2
Animation b1

- Stable against axisymmetric mode (a1, a2)
- Spirals form
- Sort of steady state?

Traditional and modern views





Summary

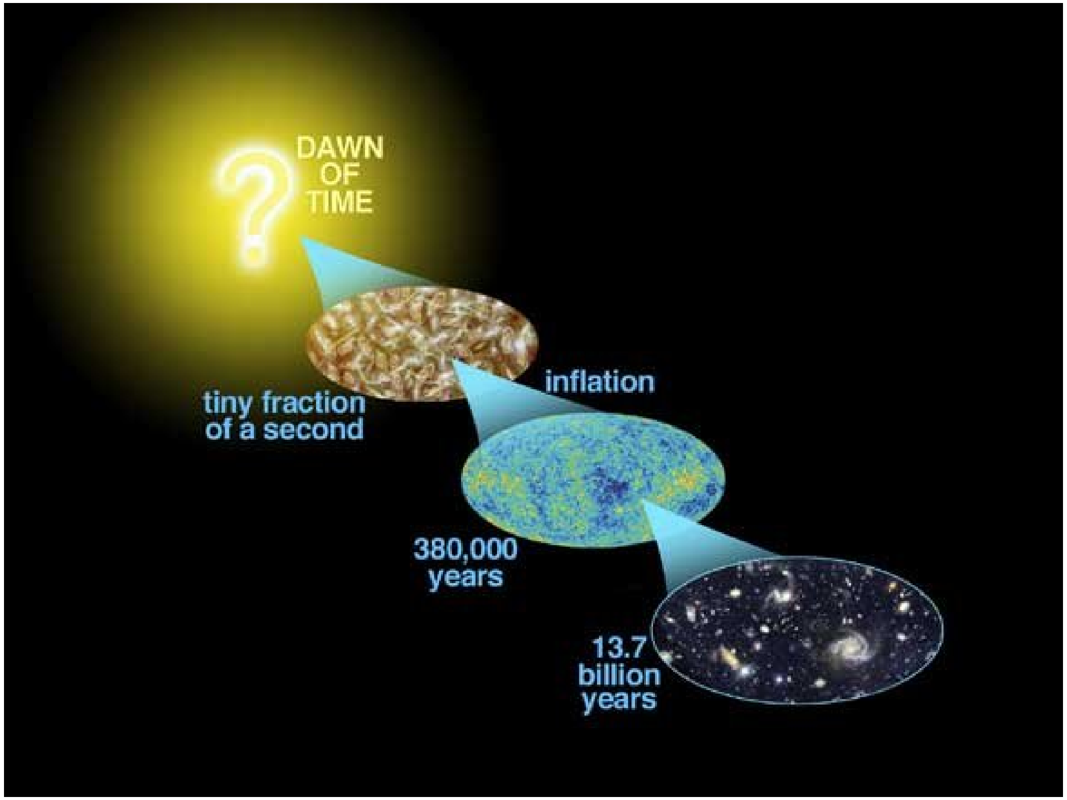
- Spiral structures are not static density waves, but time-dependent material structures
- The "winding problem" is "solved" by forming new arms continuously
- Stars and gas moves in very complex ways
- Local starbursts are probably associated to the formation and growth of new arms

Numerical Simulation of Galaxy Formation

- Tries to make galaxies from "first principles"
- Starting from initial density perturbation
- Cooling of gas and star formation, Supernova feedback, etc, are taken into account.

Would not directly reconstruct the Milky Way, but should give ways to calibrate the reconstruction of SFR from observations

Initial/boundary condition



Big bang

Small density fluctuations
→ gravitational instability
→ galaxies

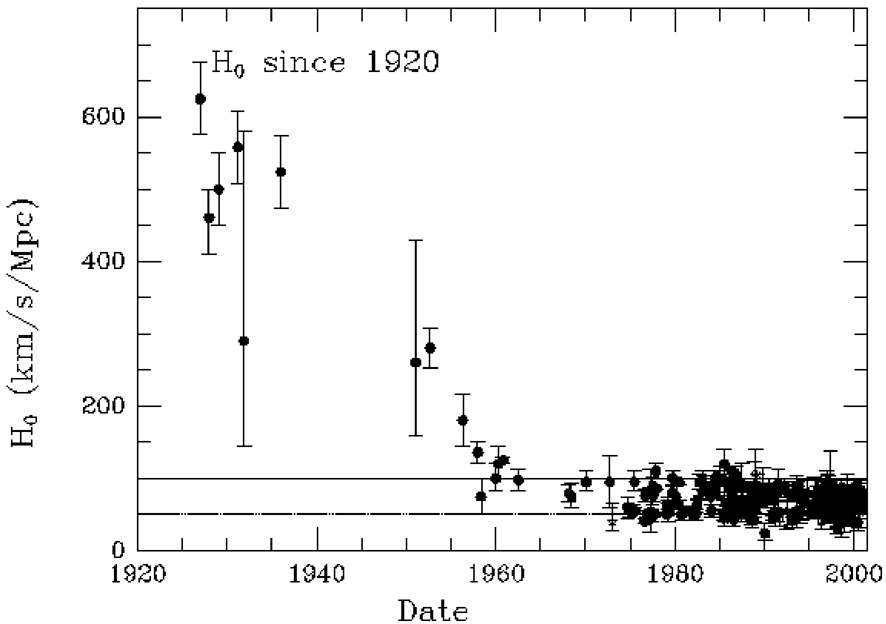
Determining initial/boundary conditions

- **How the universe as a whole behaves?**
- **What's the origin of the fluctuations from which structures evolve?**

- **Until very recently, there was no consistent model which has no serious flaw.**
- **Partly because over-interpretation of observational data...**

Variation of Hubble's "constant"

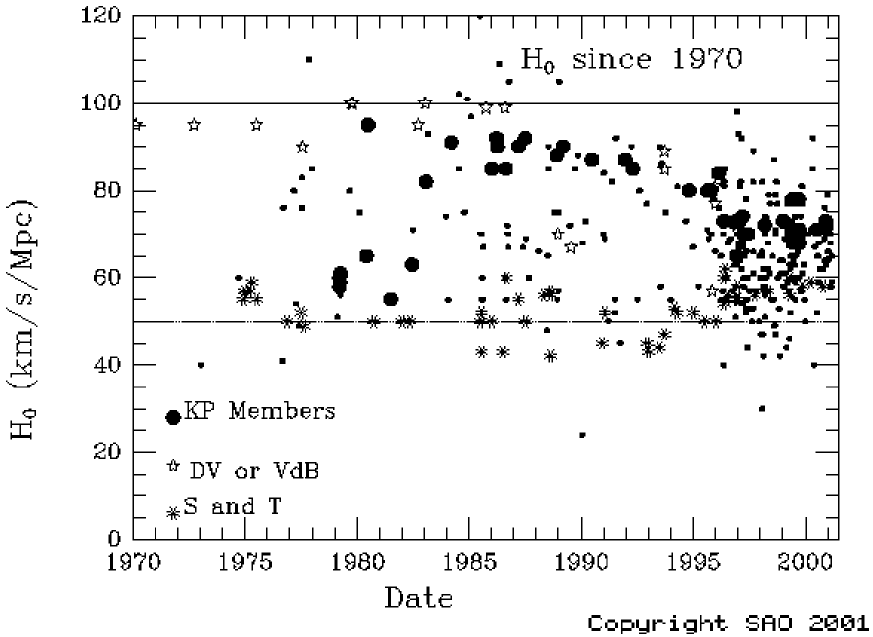
The current expansion speed of the Universe changed by a factor of 10 in the last 80 years.



Causes of large errors:

- **Wrong interpretation of the luminosity of variable stars**
- **Effect of large-scale inhomogeneity of the distribution of galaxies**
- **...**

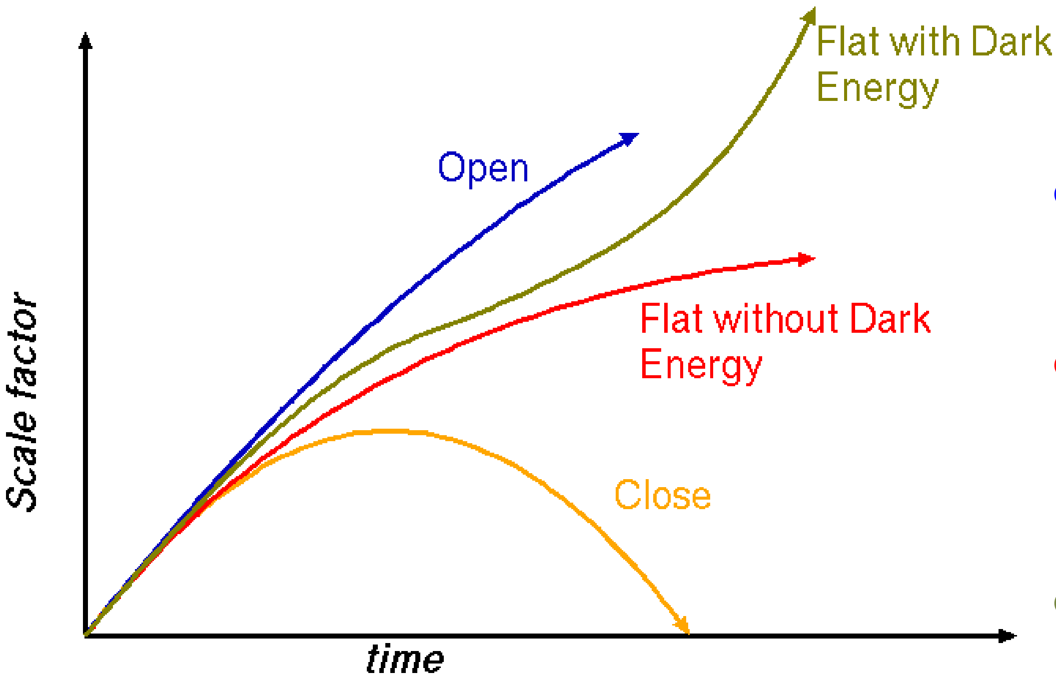
Variation of Hubble's "constant"



- **Rather surprisingly, data from different measurements "converged".**
- **Hubble Space Telescope played a very important role.**

Really accurate measurements can determine cosmological quantities reliably.

The way the universe behaves



- **Open: Universe = Baryons**
- **Flat w/o Dark Energy: = B+Dark Matter**
- **F w DE: = B+DM+DE**

Measurements of distant Supernovae and other data rejected everything other than F w DE. (2011 Novel Prize)

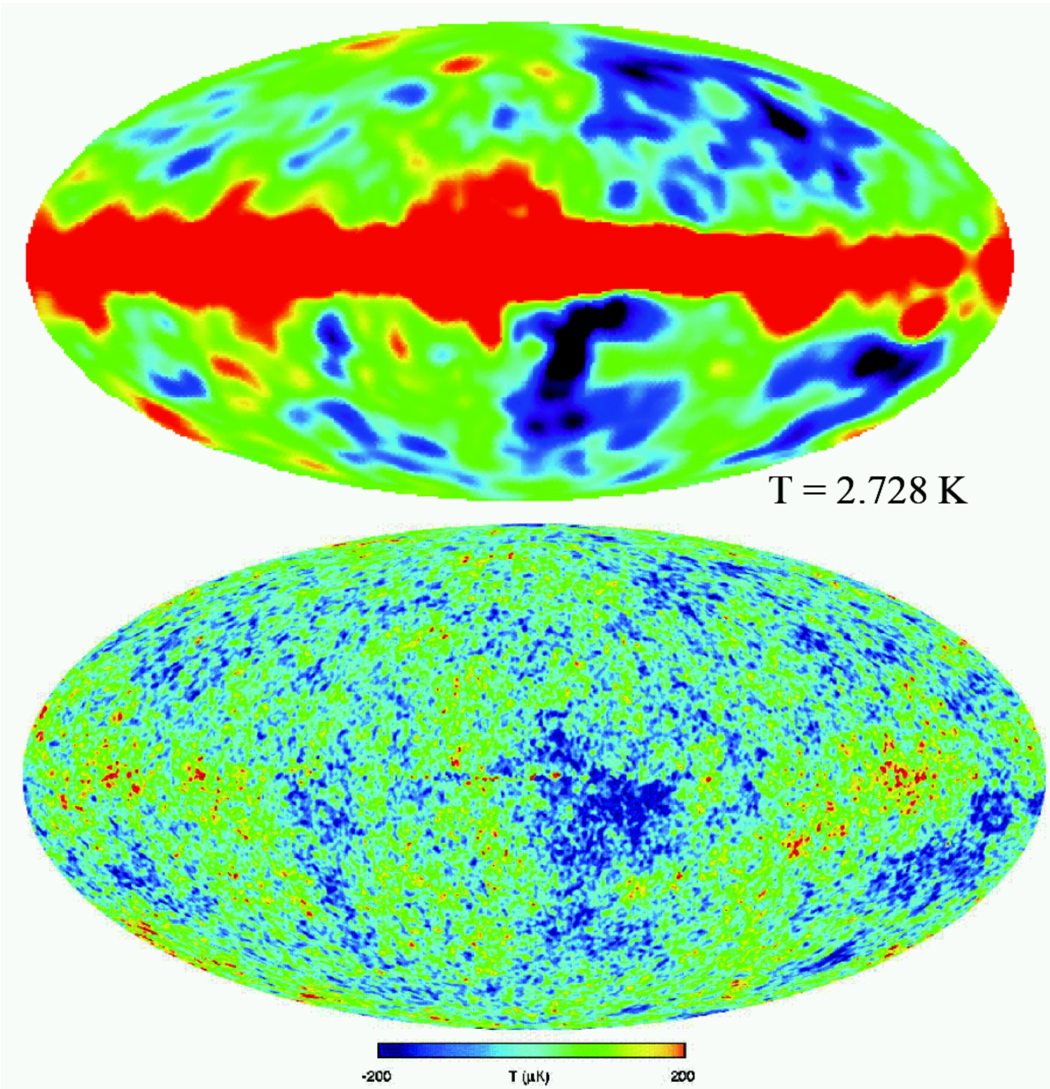
Current value: 5% Baryons, 18% DM, 73% DE.

Origin of density fluctuation

- Thermal fluctuation
  - Hot dark matter (Neutrino)
  - Cold dark matter (Unknown elementary particles)
    - Mixed, Self-interacting etc etc...
- Domain defects (Cosmic strings)
- others...

High-accuracy measurements provided us sufficient data to resolve the issue...
SDSS, WMAP, etc etc ...

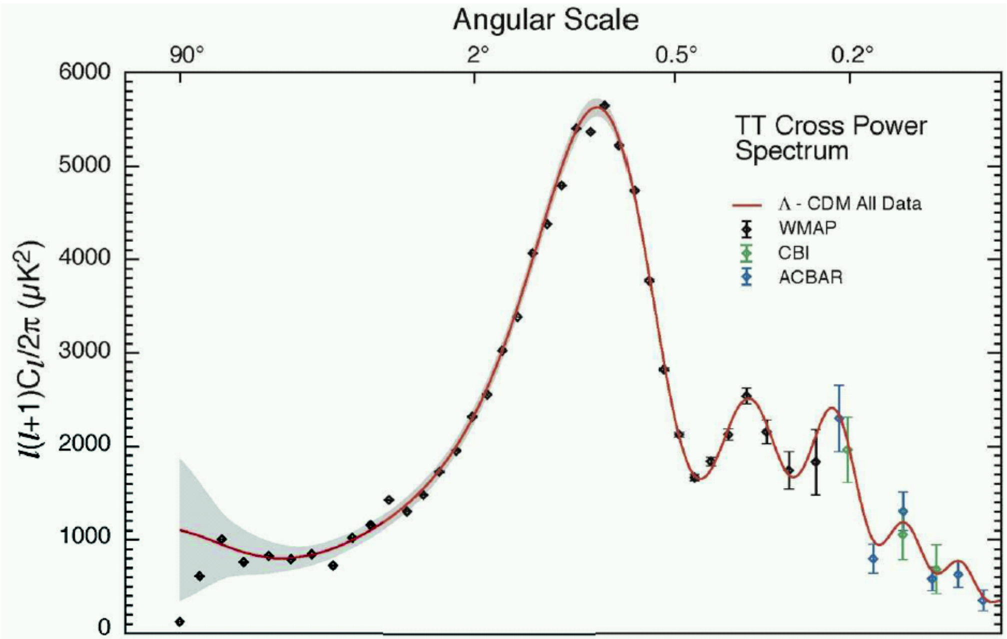
WMAP observation



COBE (1993): For the first time, fluctuation of cosmic microwave background actually measured.

WMAP (2003-): Much higher resolution and accuracy

WMAP power spectrum



Theoretical prediction (Flat, CDM+DE, Thermal fluctuation) agrees with observational data very well

(almost too well...)

“Concordance” Cosmology

For the first time in the history of modern science, we have one consistent view of the universe.

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- **Flat universe with dark matter and dark energy**
- **Cold dark matter**
- **Thermal fluctuation**

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- **Flat universe with dark matter and dark energy**
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So we now know the initial and boundary conditions.

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(*hard to believe....*)

- **Flat universe with dark matter and dark energy**
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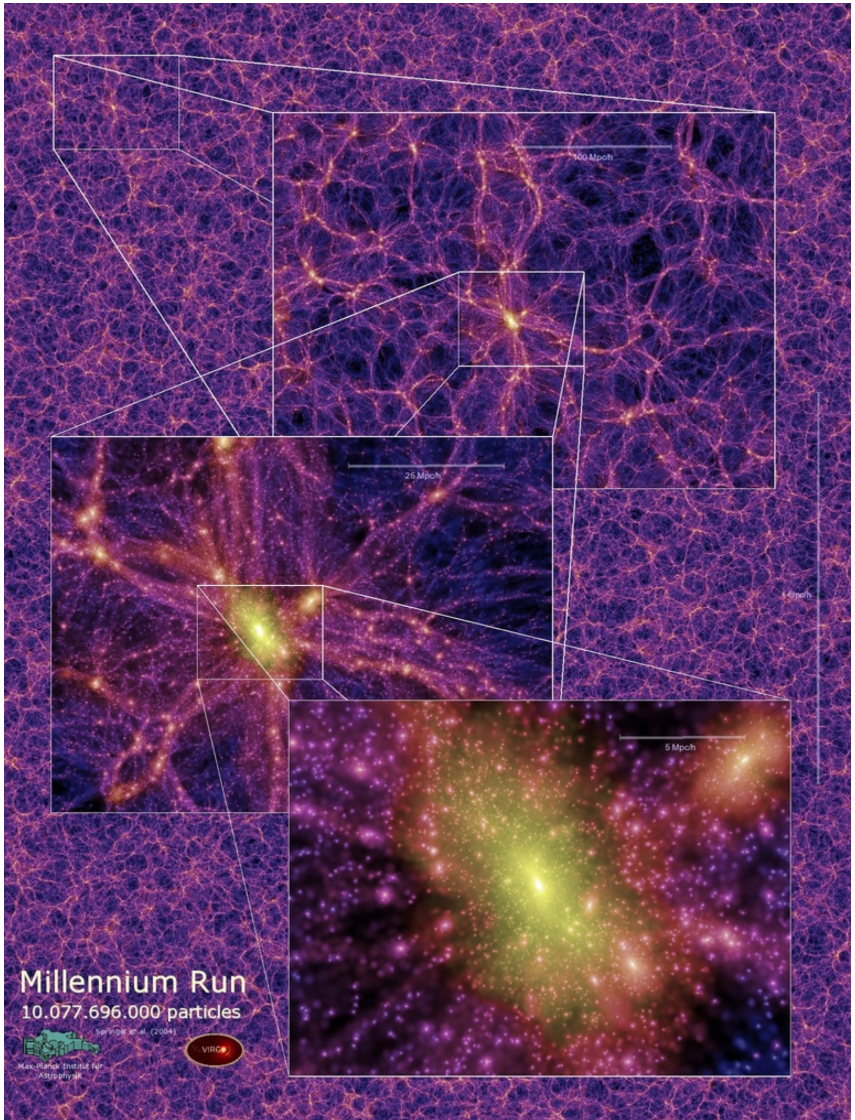
So we now know the initial and boundary conditions.

(even harder to believe...)

Solving equations

- **Structure formation through gravitational instability**
  - **“Dark Matter”, gravity and equation of motion**
- **Baryon (normal matter)**
  - **Hydrodynamics**
  - **Radiative transfer**
  - **chemical reaction**
  - **star formation and stellar evolution**
    - **nuclear reaction**
    - **...**

Dark Matter



Many-body problem

Gravitational interaction

"N-body simulation"

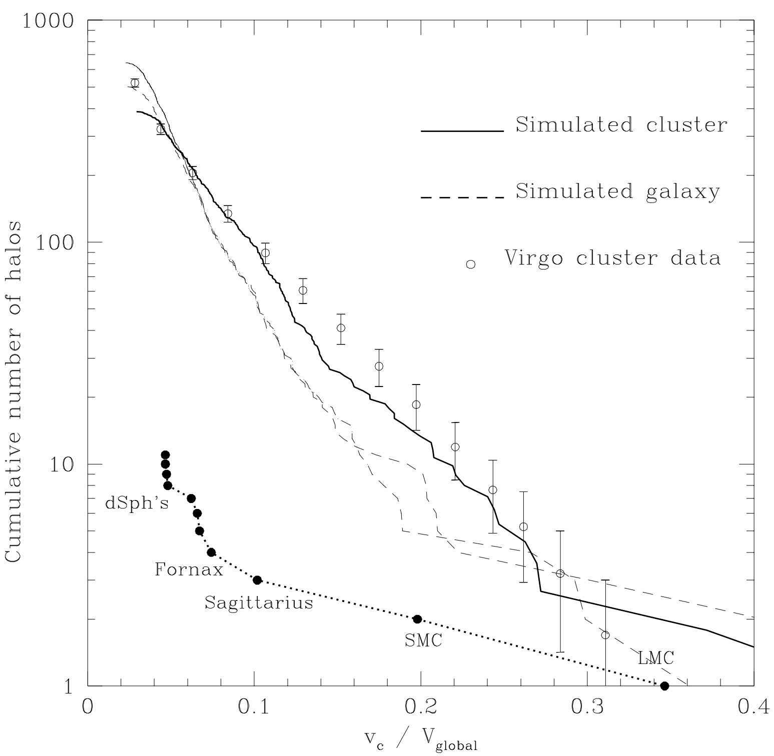
Up to 10^{10} particles

"Easy" part of the problem

Actually not so easy — The Dwarf problem

Problem:

Moore et al 1999

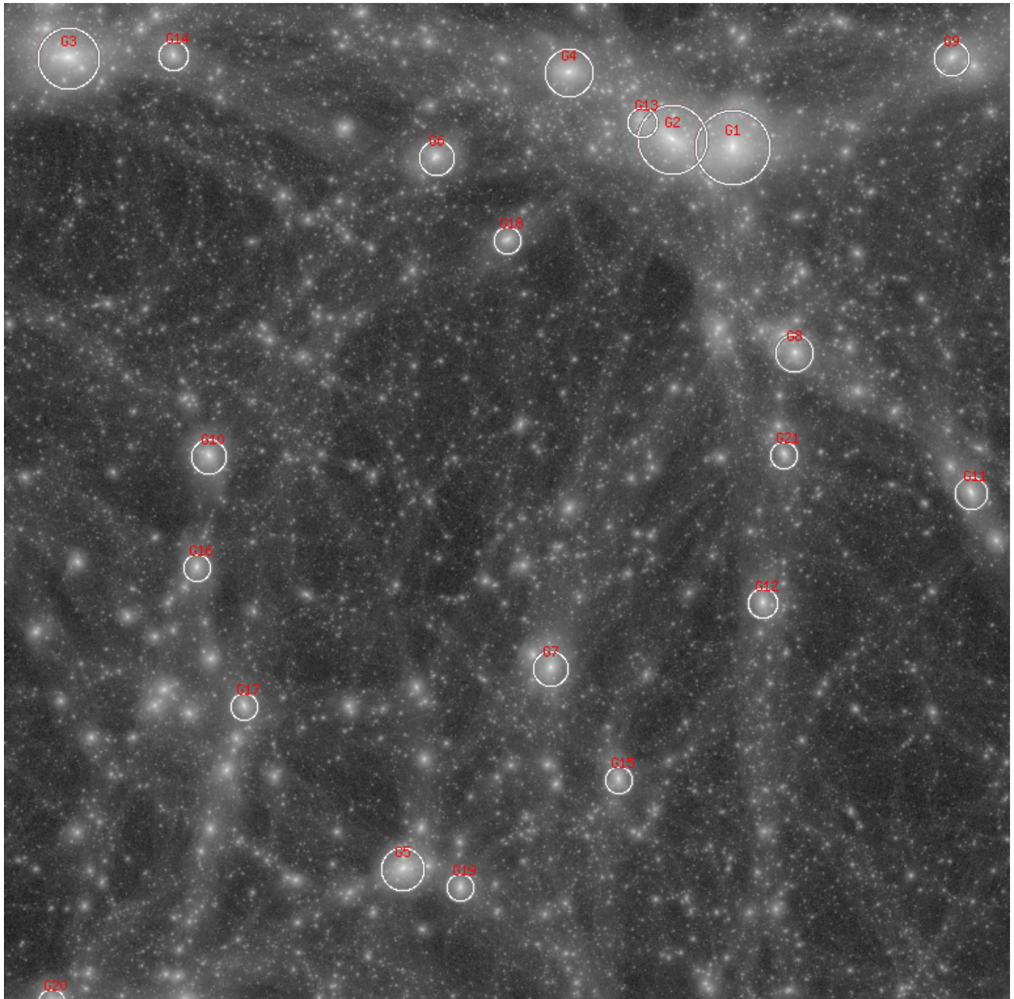


- Galaxy-size Simulated Dark-matter halos contain far too many subhalos
- Our galaxy contain only $\sim$ 10 satellite galaxies
- Why?

Ishiyama et al. 2008

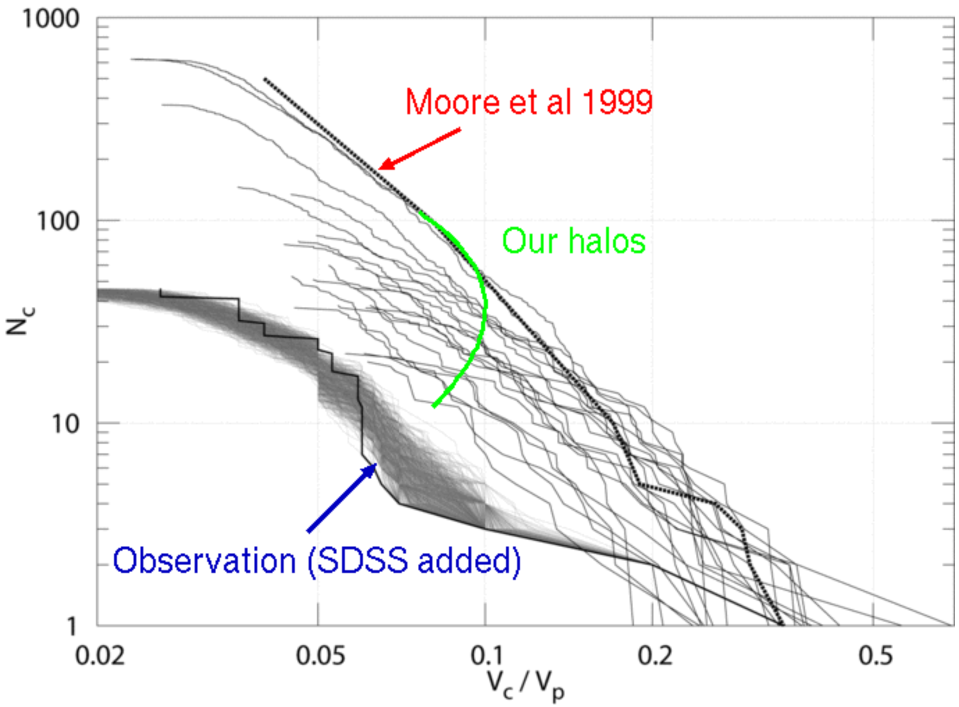
- **“Observe” all simulated halos in one simulation box**
- **GRAPE-6A cluster/PC Cluster/Cray XT4**
- **512^3 — 1600^3 particles**

512^3 and 1024^3 results



1024^3 movie

Result



- **Large variation in number of subhalos**
- **The richest ones agree with Moore's result**

The poorest ones are within a factor of two with observations

The existence of our Galaxy *may be* **consistent with the current standard cosmology.**

DM-only simulation summary

- **Current cosmology** *may be* **consistent with the existence of Milky Way, with very small number of satellite galaxies.**
- **Previous works reached to wrong conclusions primarily because of some selection bias.**
- **However, clearly it is necessary to solve the evolution of Baryons (gas and stars), to really compare with observations**

Baryon Physics and more

Two approaches

- **Detailed simulation of single galaxy**
  - **Solve hydrodynamics**
  - **Solve radiative transfer (well...)**
  - **Model star formation**
  - **....**
- **"Semi-analytic" modeling of statistical sample of galaxies**
  - **Model the Baryon physics within each "Dark halo" as "sub-grid physics"**
  - **make statistical comparison with observations**

I'll discuss detailed simulations.

Examples of recent detailed simulations

Saitoh et al. 2004

- **SPH (Smoothed Particle Hydrodynamics)+N-body**
- **10^6 SPH particles**
- **10^6 Dark-Matter particles**
- **11-months calculation on a GRAPE-5 special-purpose computer**

Galaxy Formation

Limitation of current galaxy-formation simulations

- **Limited mass resolution $\rightarrow$ cannot express low-temperature, high-density interstellar gas (Gas temperature $> 10^4$K)**
- **Cannot express gas compression due to shock**
- **Cannot express starbursts....**

Cannot say much about the SFR history....

Example of limitation

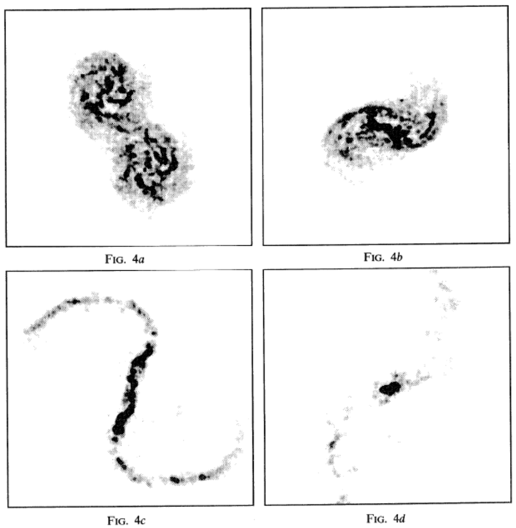
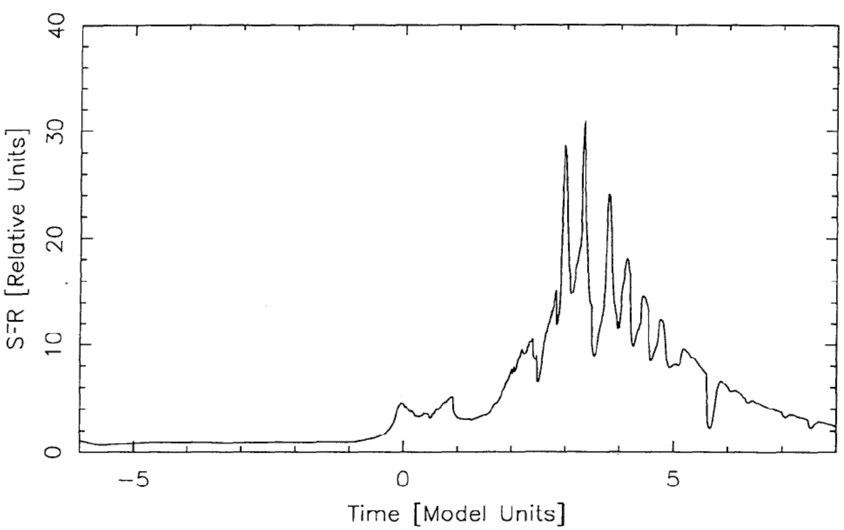


FIG. 4.—Star formation maps of a prograde-prograde merger. Each galaxy rotates clockwise; the orbital motion is clockwise as well. (a) $T = -1.1$, (b) $T = 0.3$, (c) $T = 1.7$, (d) $T = 3.1$.



Mihos et al. 1992
Simulation of merging of two disk galaxies
10^4 SPH particles

Starburst occurs only after two galaxies merged completely.

Starbursts are observed in many interacting galaxies in stages well before the final merging.

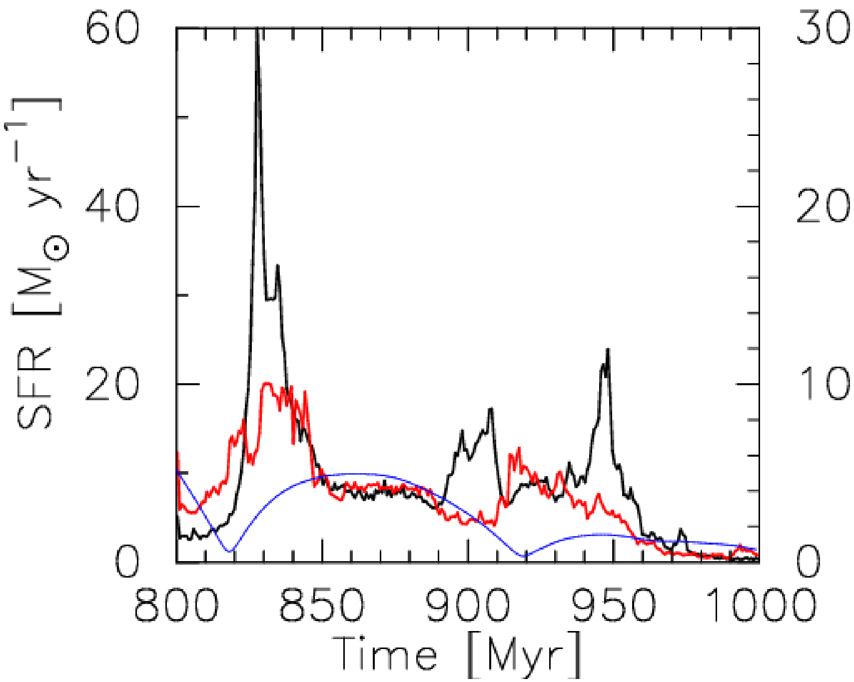
Ultra-high-resolution simulation

Saitoh et al. 2008, 0.6M SPH particles, 16M dark matter particles

- **32-node Cray XT4, less than one month**
- **Gas cooling calculated down to 10K**
- **Star Formation occurs only in very dense gas**

Animation 1 Animation 2

Star formation history



Starburst occurs at the first encounter and also at the second encounter

For the first time, numerical simulation reproduced interaction-induced starburst

Summary

- Star formation history in our Galaxy is pretty difficult to reconstruct.
- In principle, numerical simulation of galaxy formation can tell how we should do the reconstruction and the possible source of errors
- Until recently, simulations could not say much about star formation history, because of the uncertaininty in the initial condition and limited numerical resolution.
- Recent large-scale simulations show signs of hope.